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13. ABSTRACT (Maximum 200 words)

Research was conducted on analysis and modeling of low frequency sea surface scattering data obtained during the Acoustic Surface Reverberation Experiment (ASREX) conducted between December 1993 and March 1994 in the North Atlantic. This research contributed to the development of more accurate scattering models for the mean scattering level as a function of environmental conditions. A second result was to understand the statistical distribution of the backscattered intensity.

14. SUBJECT TERMS

sea surface bascattering, ambient noise, low frequency, Chapman-Harris model, Ogden-Erskine model, statistical distribution of intensity distribution

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Applied Physics Laboratory
College of Ocean and Fishery Sciences, University of Washington

12 October 1998

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Subj: ONR Grant N00014-96-1-0063, Final Report

Encl: (a) Appendix A: "Modeling Surface Scatter Intensity Statistics," viewgraph presentation, 17-18 October 1995
(b) Appendix B: "Modeling Low Frequency Surface Scatter Intensity Statistics," viewgraph presentation, 2-6 December 1996

Under the subject grant titled "Analysis and Modeling of ASREX Results" research was conducted on analysis and modeling of low frequency sea surface scattering data obtained during the Acoustic Surface Reverberation Experiment (ASREX). An important part of the surface scattering problem is the development of accurate scattering models for the mean scattering level as a function of environmental conditions. It is equally important, however, to understand the statistical distribution of the backscattered intensity. The main part of the research addressed this issue through modeling studies and through analysis of ASREX data. The final report for this research is given below.

BACKGROUND

The Acoustic Surface Reverberation Experiment was carried out during the period from December 1993 to March 1994 in the North Atlantic. During ASREX Harry DeFerrari and co-workers at the University of Miami measured ambient noise and low frequency sea surface backscattering at short range. In support of these acoustic measurements, extensive environmental measurements were made by other investigators. The development of a better understanding of low frequency sea surface scattering through the analysis of ASREX data was the final focus of the surface component of the Acoustic Reverberation Special Research Program (ARSRP).

For several decades the Chapman-Harris empirical model [Chapman and Harris, 1963] for average backscattering strength as a function of wind speed, frequency, and grazing angle

summarized knowledge of low frequency sea surface backscattering strength. Recently, the Critical Sea Test (CST) program has produced an improved empirical model for surface backscattering strength, the Ogden-Erskine model [Ogden and Erskine, 1992], and a large body of useful information on low frequency (100 Hz - 1 kHz) surface scattering. Important basic research questions on surface scattering, however, still remain to be answered. While it is generally agreed that rough interface scattering is the dominant scattering mechanism at the low end of the frequency range (near 100 Hz), and that scattering from bubble clouds becomes the dominant mechanism at higher frequencies and wind speeds, the environmental factors that determine the spatial distribution of air void fraction near the surface, which determines the strength and statistical distribution of the scattering, are not well understood. The Ogden-Erskine model is based on wind speed, which is the dominant environmental factor, but clearly other (presently unknown) environmental conditions are important as well.

In addition to improving our ability to predict scattering strength, it is also important to improve our understanding of (and develop models for) the statistical distribution of the surface scattered returns, particularly in the upper end of the distribution, since these returns can lead to false targets. As yet, models for the surface scatter statistical distribution have not been developed from CST measurements, though studies by Gauss and by Huster show highlights with lognormal intensity distributions in some cases. In the absence of other information, the surface scattered field statistics would likely be assumed Gaussian, which means the scattered intensity distribution would be taken as exponential. However, lognormal intensity distributions, in comparison to the exponential distribution, would lead to very different probabilities of occurrence for intensities well above the mean.

ASREX differed from CST surface scattering experiments in several respects. Probably the most important was that the equipment was moored below the surface and operated continuously for nearly three months with source transmissions every 12 minutes. This mode of operation is very good for identifying environmental dependencies and for statistical distribution studies.

There are important basic questions that arise when the issue of the backscattered intensity distribution is addressed. When the statistics are non-Gaussian, the issue cannot be simply handled by measuring the intensity distribution as a function of environmental conditions, and then using that information directly in a model. The fundamental problem is that the statistical distribution depends on the scattering area (or equivalently, on the number of scatterers) that simultaneously contributes to the received intensity. This means that the transmitted pulse length and the scattering geometry will enter into a prediction of scattered intensity statistics. A lognormal intensity distribution may result for a certain scattering patch size due to intermittency in the spatial distribution of bubble clouds, but if this area could be made sufficiently large to include a very large number of such clouds, Gaussian statistics will prevail as a result of the Central Limit Theorem. These considerations are especially important for ASREX, because the scattering range is relatively short, leading to a relatively small scattering patch size. In order to apply probability distribution information obtained from ASREX to longer range geometries, a methodology must be developed to account for differences in scattering patch size.

RESEARCH RESULTS

Work on modeling intensity statistics was done in two phases. In the first phase, an analytic model was developed, based on assuming that in the scattering area there are N (with N an integer) independent, identically distributed scatterers. For preliminary comparisons with ASREX data, the individual scatterers were assumed to have a lognormal intensity distribution. The equations defining this model are contained in the viewgraph presentation given at NRL-SSC in October 1995; a copy is included at the end of this report. The numerical results showed, as expected, that the resultant intensity distribution for N scatterers evolves from near lognormal to near exponential as N varies from small to large. In addition, the preliminary comparisons with ASREX intensity distribution data showed that by appropriately choosing the model parameters (the standard deviation of the individual scatterer lognormal intensity distribution, and the number of scatterers N) good agreement between data and model results was obtained. (See "Modeling Surface Scatter Intensity Statistics" by E.I. Thorsos, D.B. Percival, and K.M. Bader, presented at Surface SRP Meeting, October 17-18, 1995; included as Appendix A.)

The good agreement in these data-model comparisons turned out to be somewhat fortuitous, since the initial ASREX intensity distributions were produced by grouping intensities over the entire experiment in particular grazing angle bins. Thus, the environmental conditions varied considerably over the time period used to construct the distributions. In addition, the data processing algorithms introduced some intensity averaging for each transmission, which would also affect the intensity statistics.

For phase two of this work, improvements were made in the data analysis and the model. Neil Williams at the University of Miami reprocessed 800 Hz surface scattering data specifically for intensity distribution analysis, and all averaging was removed from the processing algorithms. The raw data was then supplied to APL-UW for further analysis. We carefully removed all obviously spurious data points and grouped the data in both wind speed and grazing angle bins. Unfortunately, questions still remained at the end of this effort on the quality of the ASREX data set. It was apparent that significant overall level uncertainties existed in the data set. While it is possible that the intensity distributions relative to the means are still valid, uncertainty in this regard led to the decision not to publish the results of this analysis.

The model was improved in the phase two analysis by removing the rather artificial assumption that the number of scatterers in the scattering area was an integer N. More realistically, the average number of scatterers $\langle N \rangle$, not necessarily an integer, is specified together with a model for the pdf of N. If one makes the simplest assumption that the scatterers are spatially uncorrelated, then it follows that the number of scatterers in the scattering area should be Poisson distributed. Using this assumption an analytical model for the intensity distribution has been developed, and a Monte Carlo implementation of the model was also been made. The two models give excellent agreement (see viewgraphs discussed below).

Results of the phase two analysis were presented at the Acoustical Society Meeting in December 1996, and copies of the viewgraphs are included at the end of this report. [Thorsos, Percival, and Bader, 1996; see Appendix B.] For this intensity statistics analysis, only data points with SNR > 15 dB were used. No intensity distribution variation was noted over the grazing angle range from

10 deg to 30 deg, and therefore the intensity distributions over this grazing angle range were combined. The scattering area on the surface ranged from 20,000 to 40,000 square meters.

The ASA viewgraphs summarize the results. At low wind speed (up to 5 m/s) the intensity distributions were found to be fit very well with an exponential distribution. This means the field statistics are Gaussian. At these low wind speeds, the scattering should be from the rough sea surface and scattering from bubbles should not be important. The exponential distribution for sea surface scattering implies that the rough sea surface has a large number of scatterers within the scattering area. At high wind speeds the intensity distribution deviates from exponential with a higher upper tail. This is the regime of bubble cloud scattering.

The model described above was used to fit the high sea state distributions. This can be done assuming the scattering area contains a set of identical scatterers that scatter with a lognormal intensity distribution, and the number of scattering is Poisson distributed. Good agreement is found with eight scatterers on average for the ASREX geometry, and for the scatterer intensity distribution to have a standard deviation of 5.0 -5.5 dB. To fully test such a model, data sets are needed for a range of scattering areas.

REFERENCES

Chapman, R. P. and J. H. Harris, Surface backscattering strengths measured with explosive sound sources, J. Acoust. Soc. Am. **34**, 1592-1597, 1962.

Ogden, P. M. and F. T. Erskine, An empirical prediction algorithm for low-frequency acoustic surface scattering strengths, Naval Research Laboratory technical report NRL/FR/5160-92-9377, April 28 1992.

Thorsos, E. I., D. B. Percival, and K. M. Bader, "Modeling low-frequency surface scatter intensity statistics," J. Acoust. Soc. Am. **100**, 2799 (1996)

Eric I. Thorsos

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cc: ONR Administrative Grants Officer (June Hawley), 1 copy memo, copy of Form 298, copy of DTIC Card
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Defense Technical Information Center, 2 copies of memo, enclosures, 298 Form, and DTIC 50 Card
Grants & Contracts, University of Washington (Sinh Simmons), 1 copy memo

Modeling Surface Scatter Intensity Statistics

Appendix A

Eric I. Thorsos

Don B. Percival

Kate M. Bader

Applied Physics Laboratory
College of Ocean and Fishery Sciences
University of Washington
Seattle, WA

Surface SRP Meeting
October 17–18, 1995
NRL-SSC

Introduction

- Scattering strength $\leftrightarrow$ average scattered intensity
- Need model for intensity pdf
- Cannot simply measure intensity pdf for direct use in model
  - Intensity pdf depends on the scattering area (i.e., on the number of scatterers)

Modeling issue: Predict intensity pdf for large scattering area when pdf is measured for small scattering area

Gaussian Statistics

- **Notation:**

  Complex field: $X + iY$

  Magnitude: $R = \sqrt{X^2 + Y^2}$

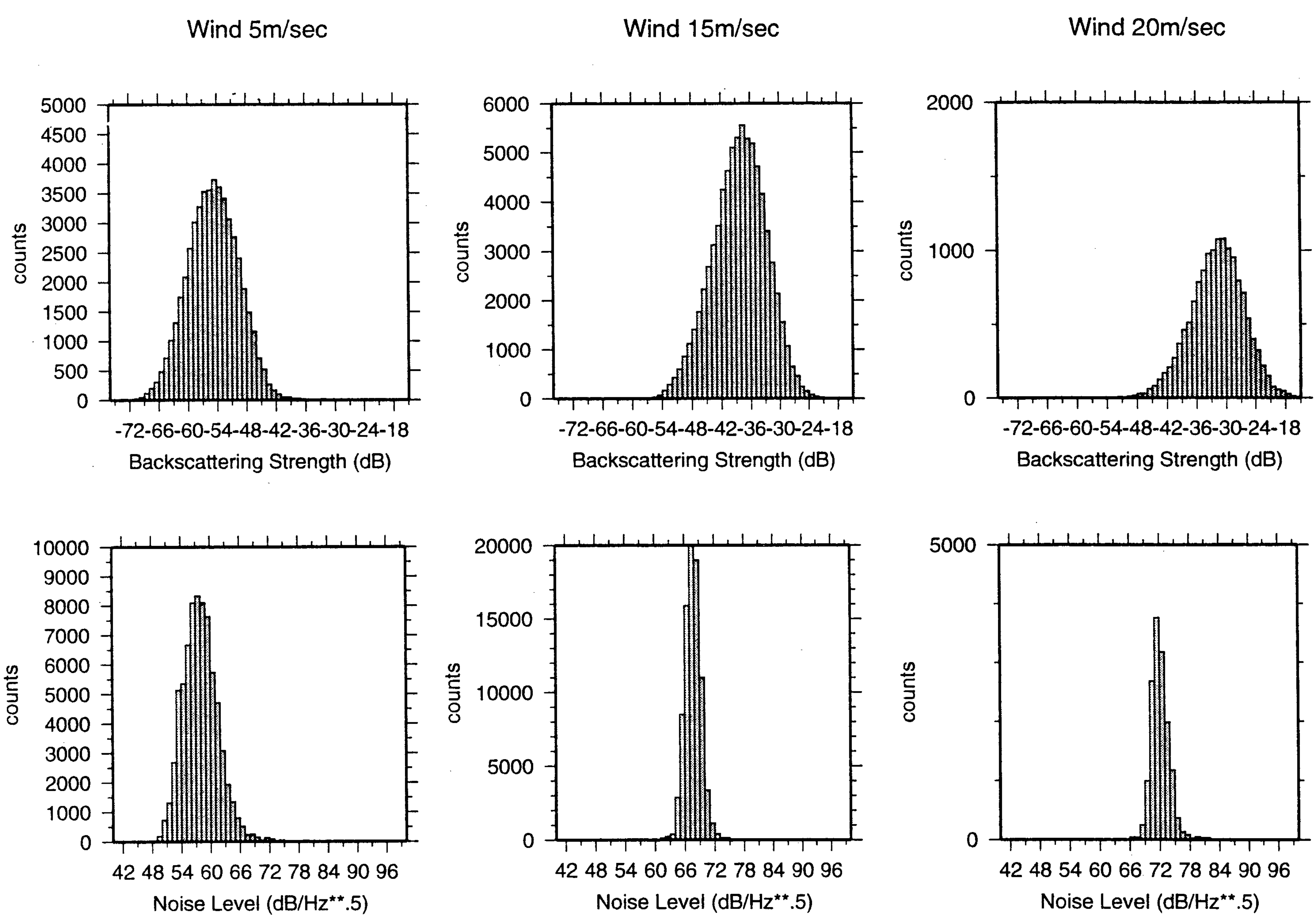
  Intensity: $I = R^2 = X^2 + Y^2$

- **When large number of scatterers contribute to field**
  - **X and Y are Gaussian distributed**
  - **R is Rayleigh distributed**
  - **I is exponentially distributed**

- **In this case, pdfs are independent of geometry**

For ASREX, I is not exponential

— Closer to lognormal



800 Hz 10 -> 20 DEG BIN

[Monjo et al., 1995]

Intensity Level PDF

- **Exponential pdf:**

$$P_I(I) = \frac{1}{\langle I \rangle} e^{-I/\langle I \rangle}$$

- **Lognormal pdf:**

$$P_I(I) = \frac{1}{\sqrt{2\pi}\,\sigma I} e^{-(\ln I - \eta)^2/(2\sigma^2)}$$

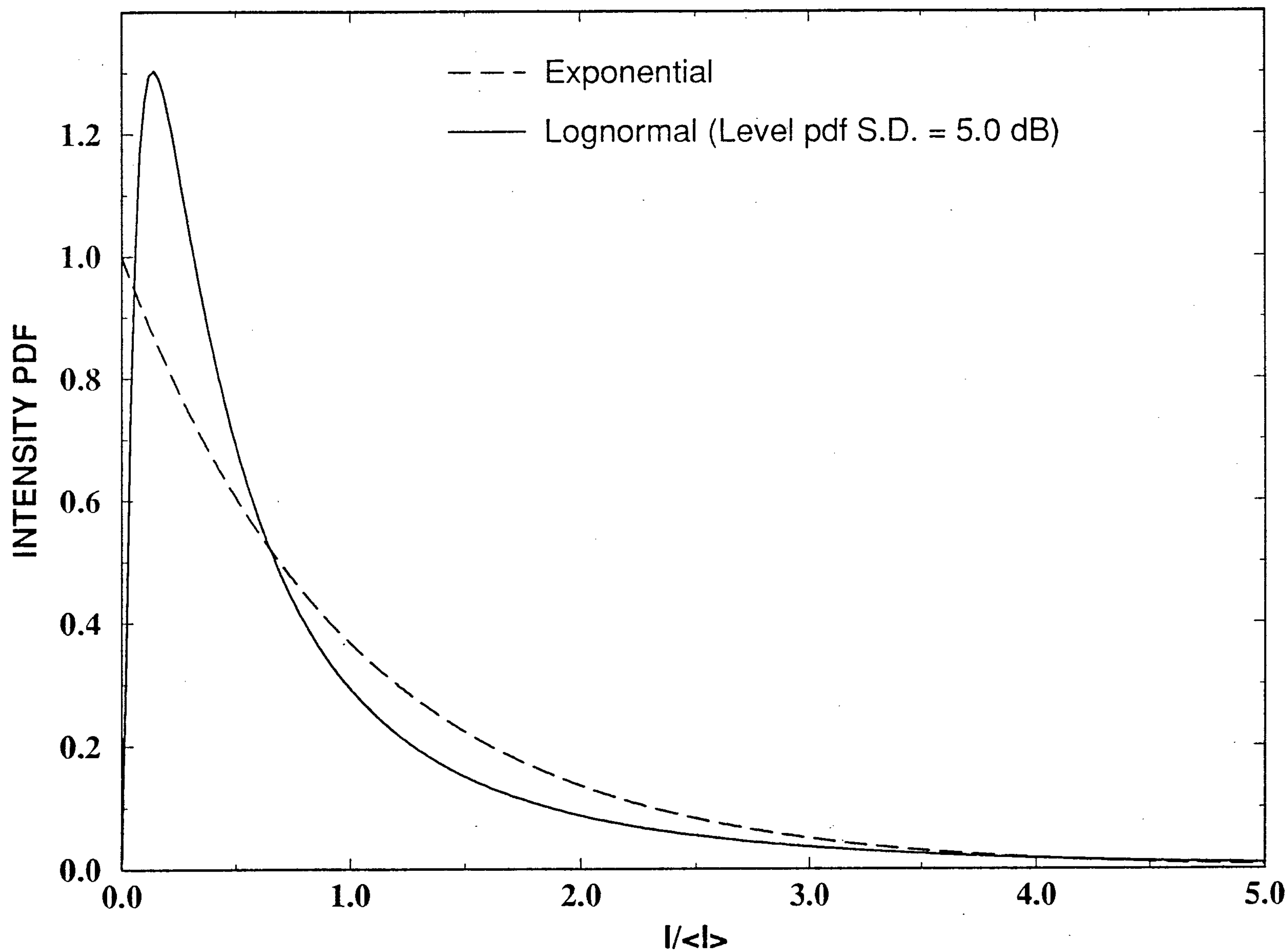
where η is mean and σ is standard deviation of normal distribution for $\ln I$

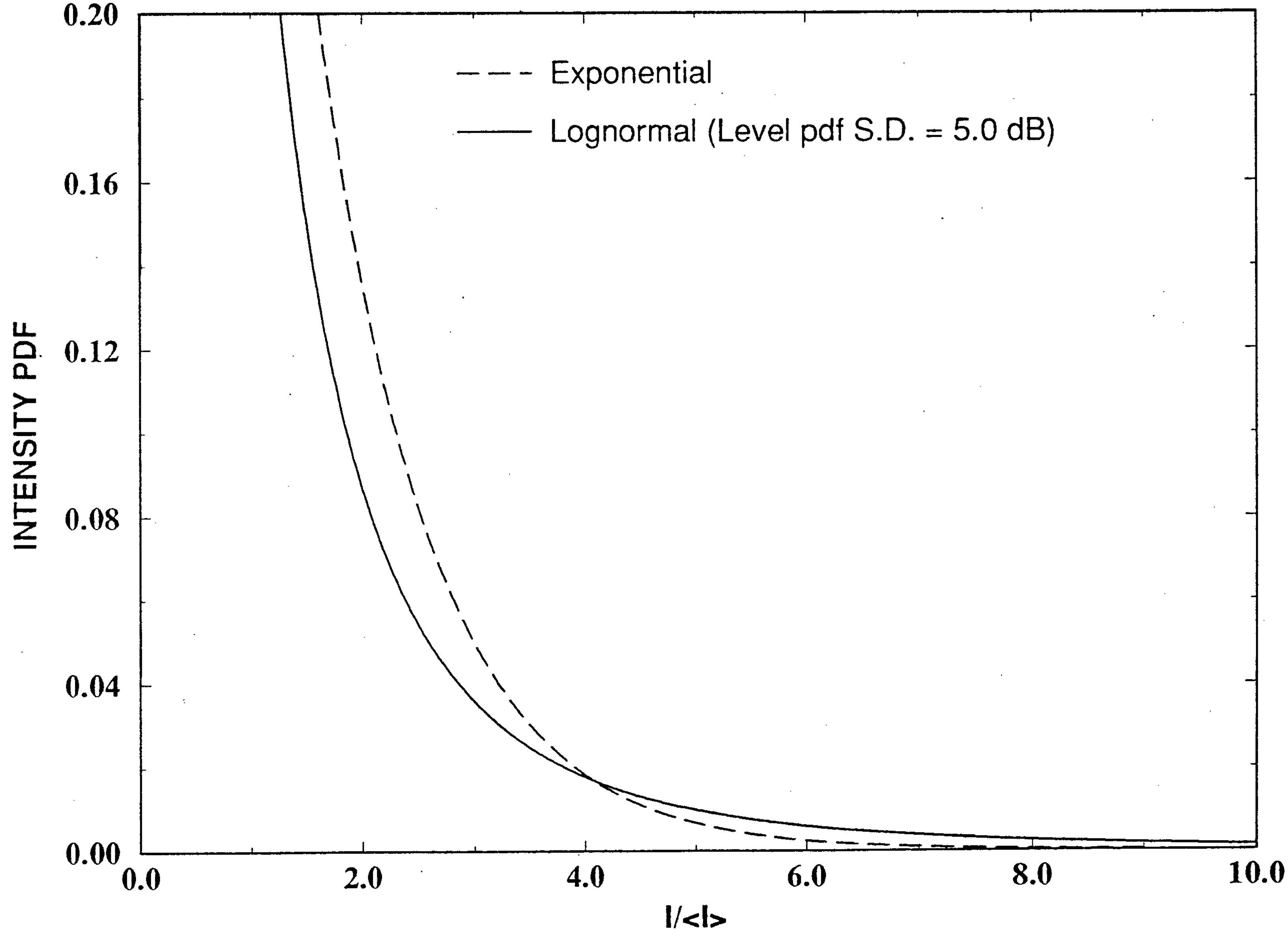
- **Intensity level:**

$$L = 10 \log_{10}(I/\langle I \rangle)$$

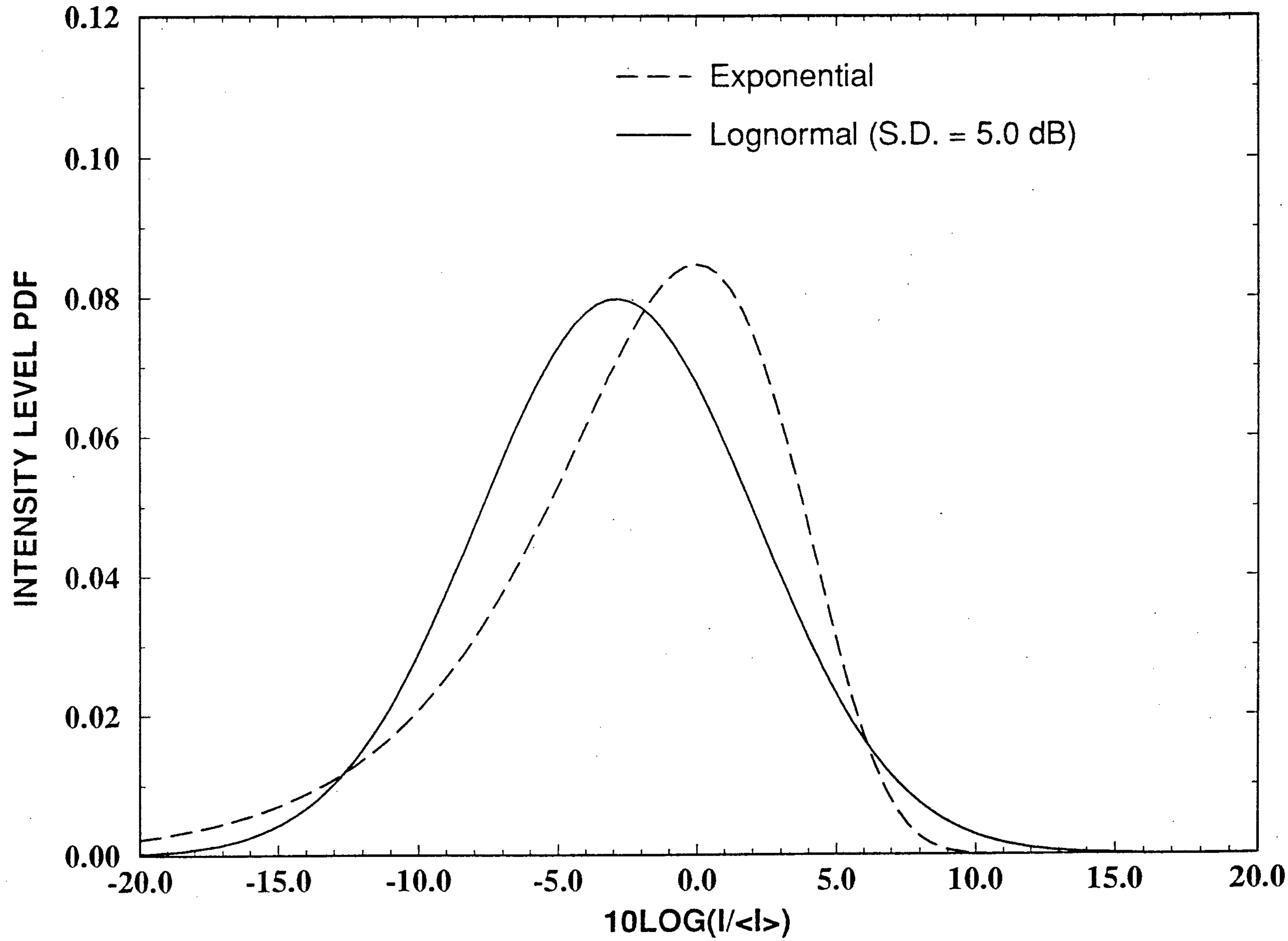
Intensity level pdf $\leftrightarrow$ pdf of L

[for convenience, $\langle I \rangle = 1$]


Exponential
Lognormal (Level pdf S.D. = 5.0 dB)
INTENSITY PDF
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
1.0
2.0
3.0
4.0
5.0
I/<I>



Exponential
Lognormal (Level pdf S.D. = 5.0 dB)
INTENSITY PDF
0.20
0.16
0.12
0.08
0.04
0.00
0.0
2.0
4.0
6.0
8.0
10.0
I/<I>



Exponential
Lognormal (S.D. = 5.0 dB)
INTENSITY LEVEL PDF
0.12
0.10
0.08
0.06
0.04
0.02
0.00
-20.0
-15.0
-10.0
-5.0
0.0
5.0
10.0
15.0
20.0
10LOG(I/<I>)

Model for Intensity PDF

- **Need pdf for total intensity**

  $$I = X^2 + Y^2$$

  where

  $$X + iY = \sum_{n=1}^{N} (X_n + iY_n)$$

- **Assume**
  - $X_n + iY_n$ is independent of $X_m + iY_m$ $(n \neq m)$
  - **Contribution from each scatterer has lognormal intensity distribution**

- **Need joint distribution $P_{X,Y}(X,Y)$ for single scatterer**

  Let $X = R \cos \phi$

  $Y = R \sin \phi$

- **Assume**

  $$P_{R,\phi}(R,\phi) = P_R(R) P_\phi(\phi) = \frac{1}{2\pi} P_R(R)$$

Model for Intensity PDF (continued)

- **Joint characteristic function: 1 scatterer**

$$\phi_{X,Y}(u_1, u_2) = \int_{-\infty}^{\infty} dX \int_{-\infty}^{\infty} dY \, P_{X,Y}(X,Y)\, e^{i(u_1 X + u_2 Y)}$$

- **Joint characteristic function: N scatterers**

$$\phi_{X,Y,N}(u_1, u_2) = \left[\phi_{X,Y}(u_1, u_2)\right]^N$$

- **Joint pdf for total field**

$$P_{X,Y,N}(X,Y) = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} du_1 \int_{-\infty}^{\infty} du_2 \, \phi_{X,Y,N}(u_1, u_2)\, e^{-i(u_1 X + u_2 Y)}$$

$\rightarrow$ **total intensity pdf**

$\rightarrow$ **average intensity pdf**

Model for Intensity PDF (continued)

- **Joint characteristic function: 1 scatterer**

$$\phi_{X,Y}(u) = \int_0^\infty dI \, P_I(I) \, J_0\left(\sqrt{I}\, u\right)$$

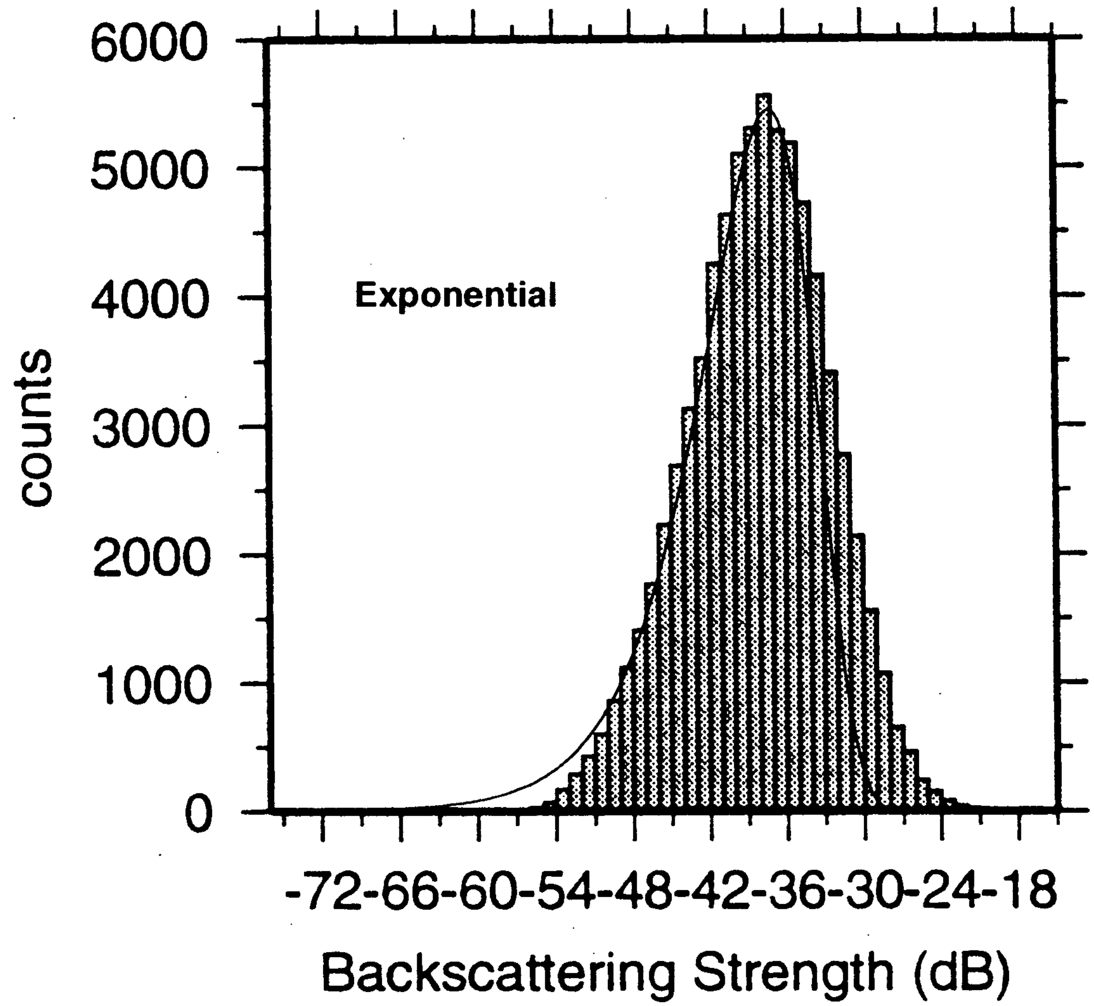
- **Joint characteristic function: N scatterers**

$$\phi_{X,Y,N}(u) = \left[\phi_{X,Y}(u)\right]^N$$

- **Average intensity pdf**

$$P_{I,N}(I) = \frac{N}{2} \int_0^\infty du \, u \, \phi_{X,Y,N}(u) \, J_0\left(\sqrt{NI}\, u\right)$$

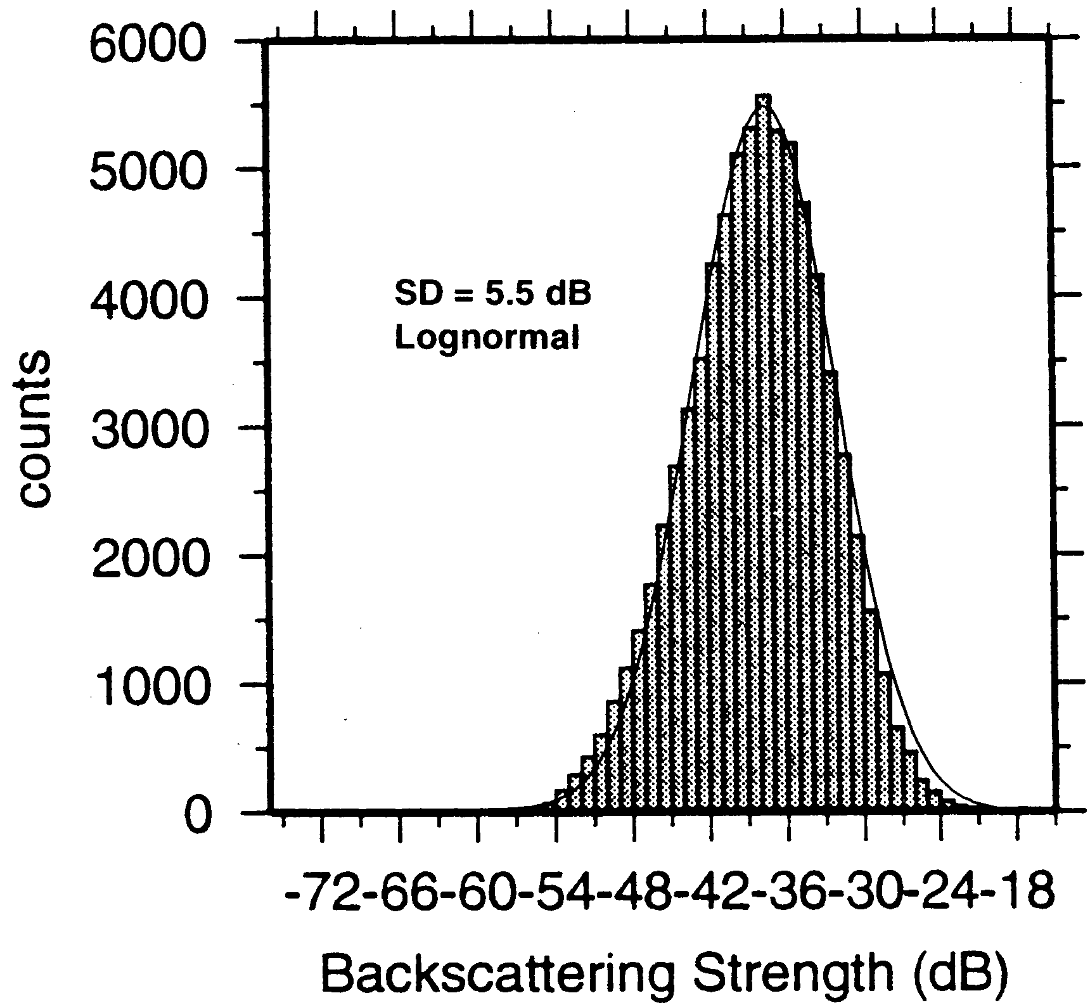
Wind 15m/sec



800 Hz 10 -> 20 DEG BIN

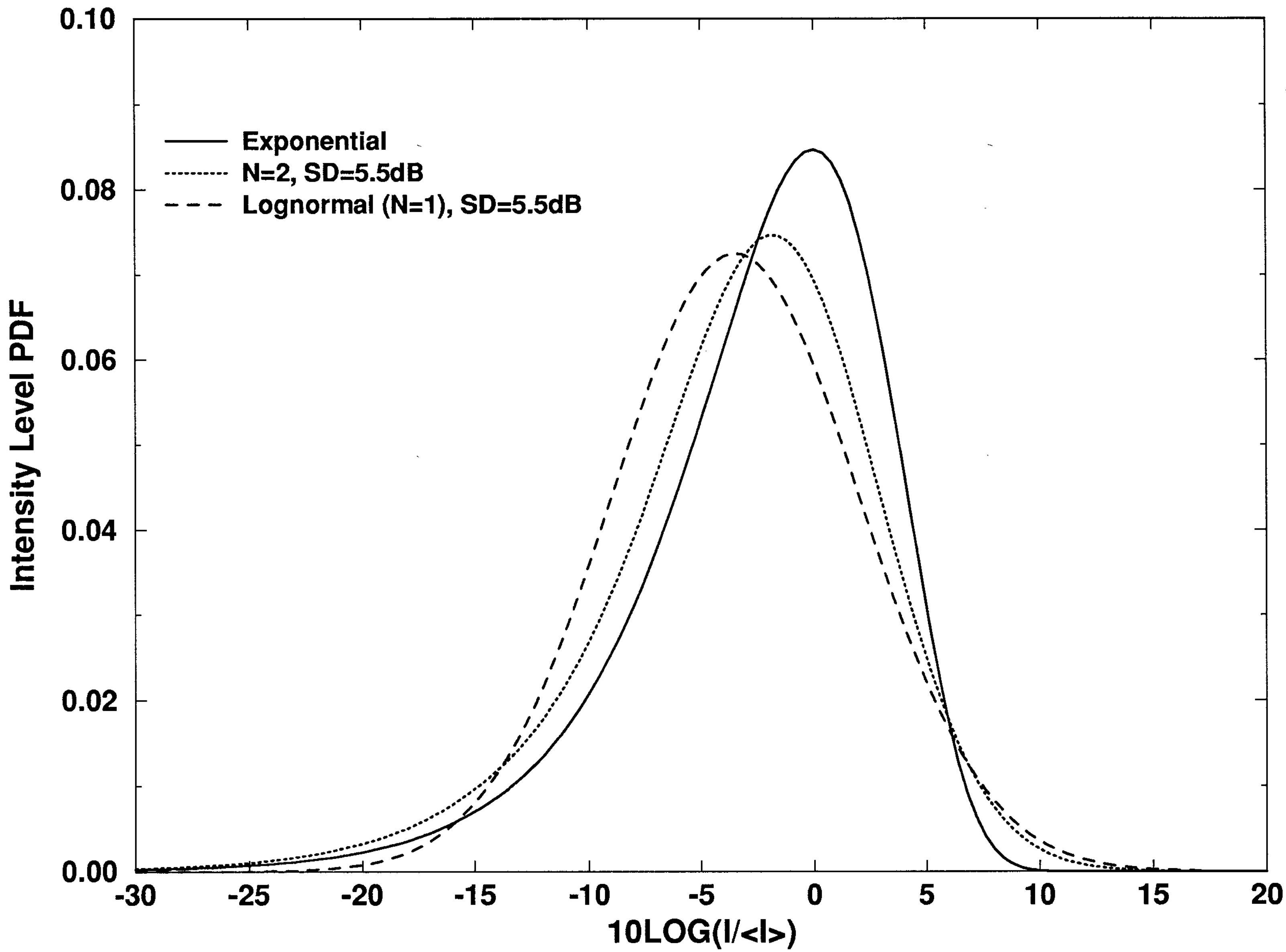
[Monjo et al., 1995]

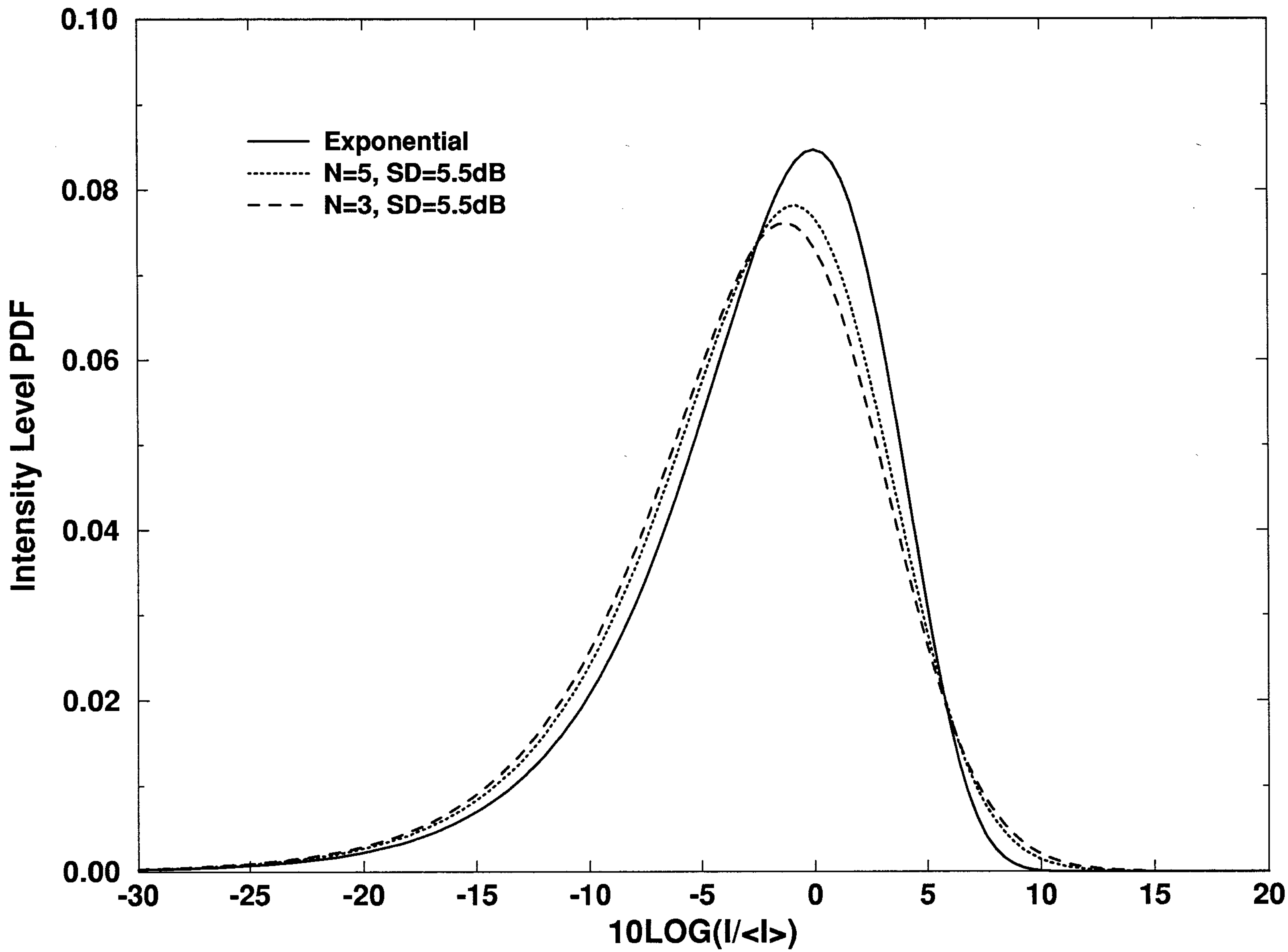
Wind 15m/sec



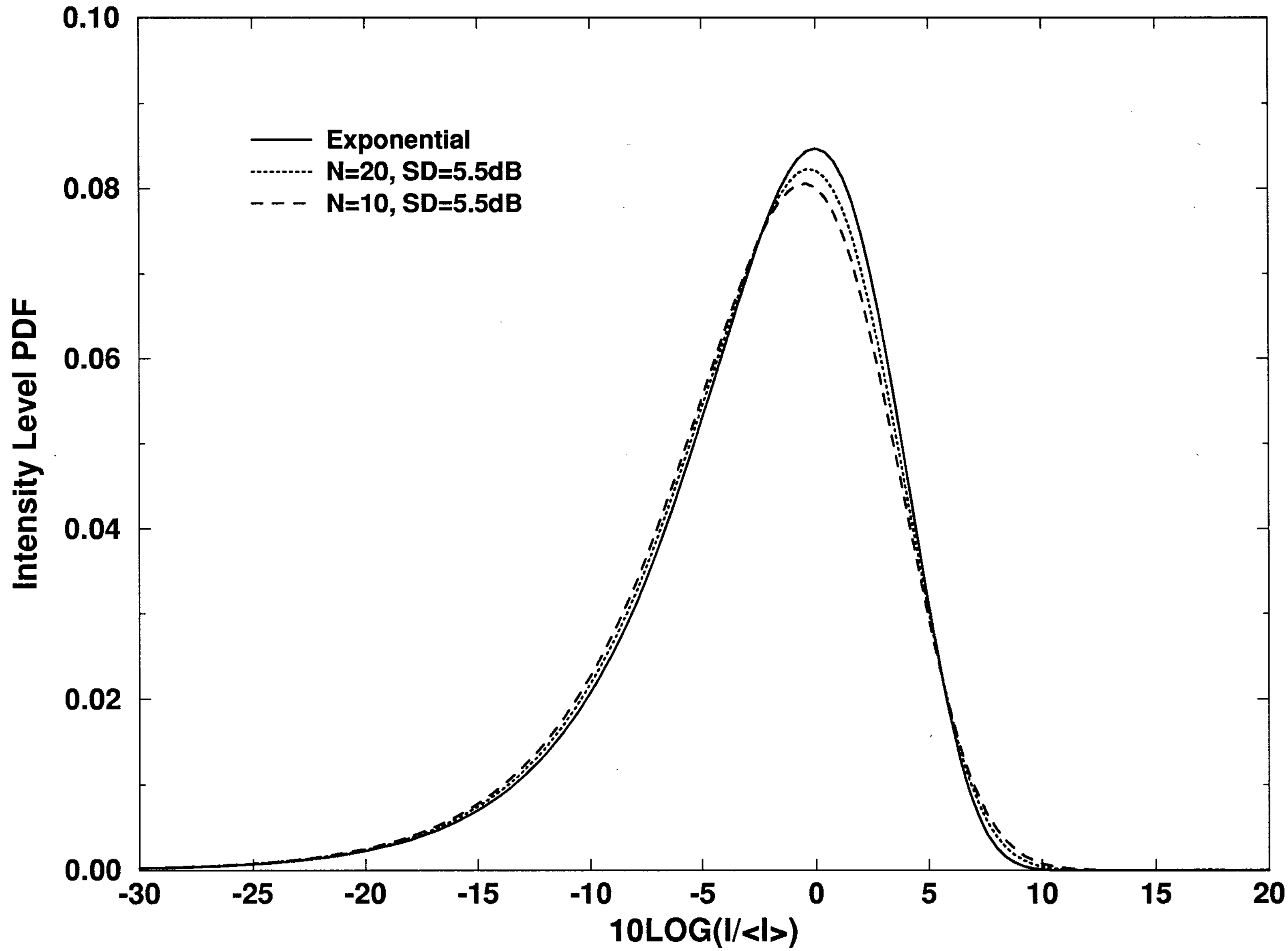
800 Hz   10 -> 20 DEG BIN

[Monjo et al., 1995]

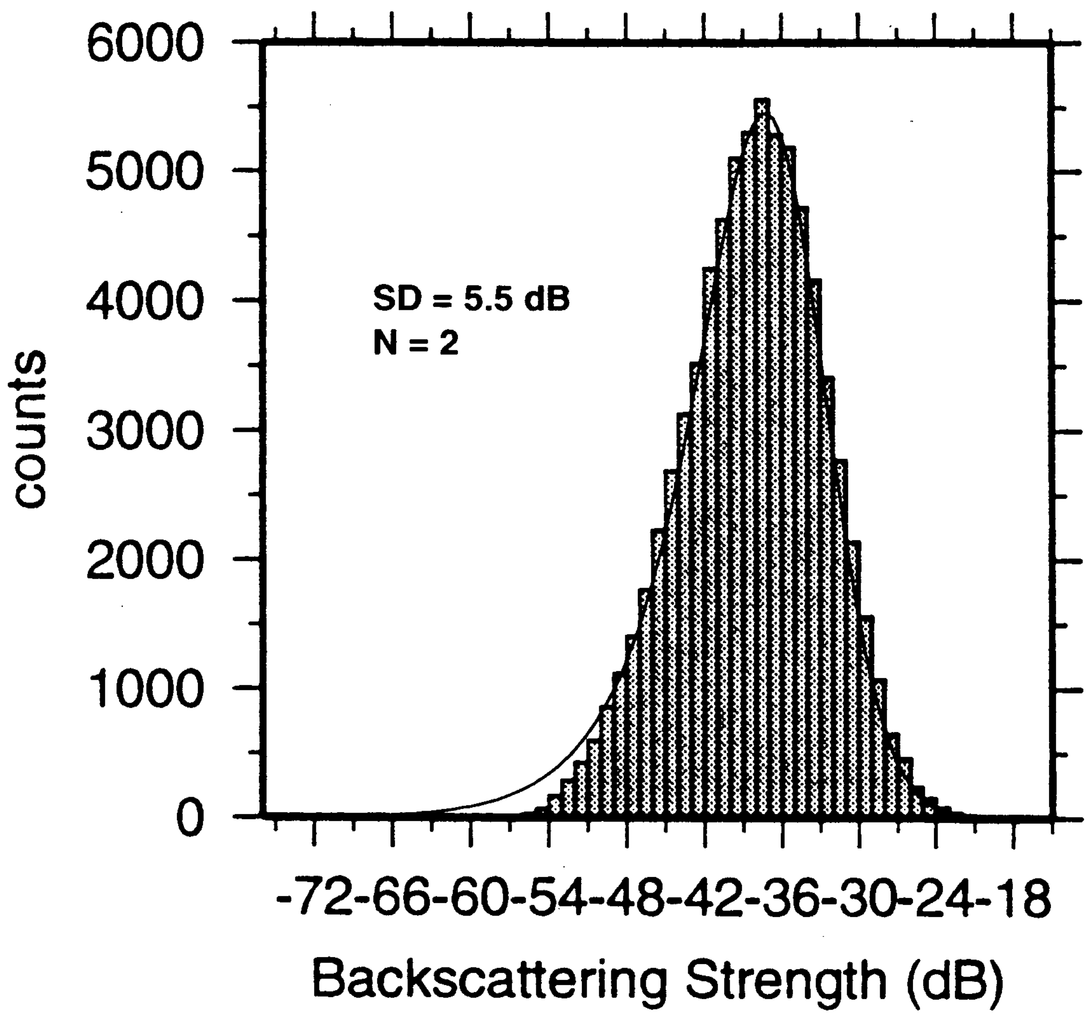

Exponential
N=2, SD=5.5dB
Lognormal (N=1), SD=5.5dB
Intensity Level PDF
0.10
0.08
0.06
0.04
0.02
0.00
-30
-25
-20
-15
-10
-5
0
5
10
15
20
10LOG(I/<I>)



Exponential
N=5, SD=5.5dB
N=3, SD=5.5dB
Intensity Level PDF
0.10
0.08
0.06
0.04
0.02
0.00
-30
-25
-20
-15
-10
-5
0
5
10
15
20
10LOG(I/<I>)


Exponential
N=20, SD=5.5dB
N=10, SD=5.5dB
Intensity Level PDF
0.10
0.08
0.06
0.04
0.02
0.00
-30
-25
-20
-15
-10
-5
0
5
10
15
20
10LOG(I/<I>)

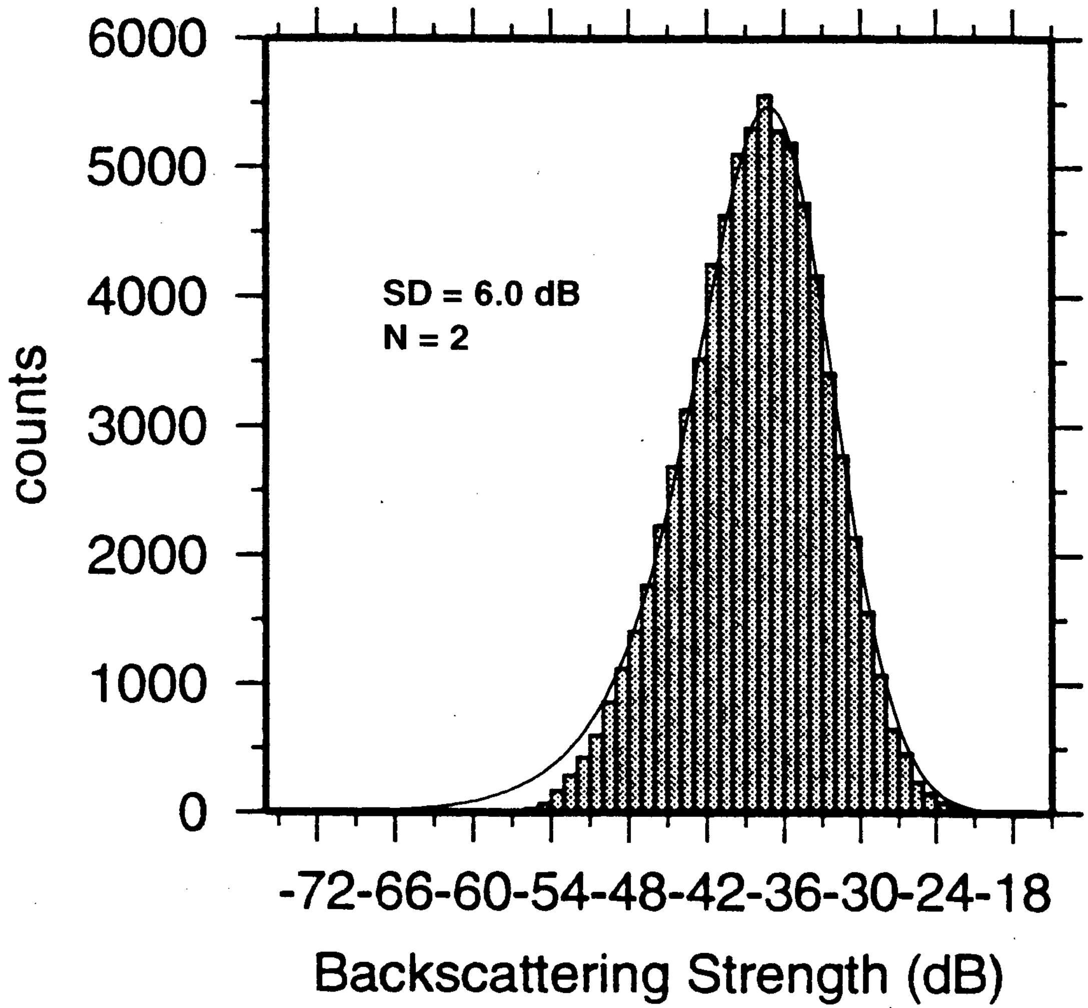
Wind 15m/sec



800 Hz   10 -> 20 DEG BIN

[Monjo et al., 1995]

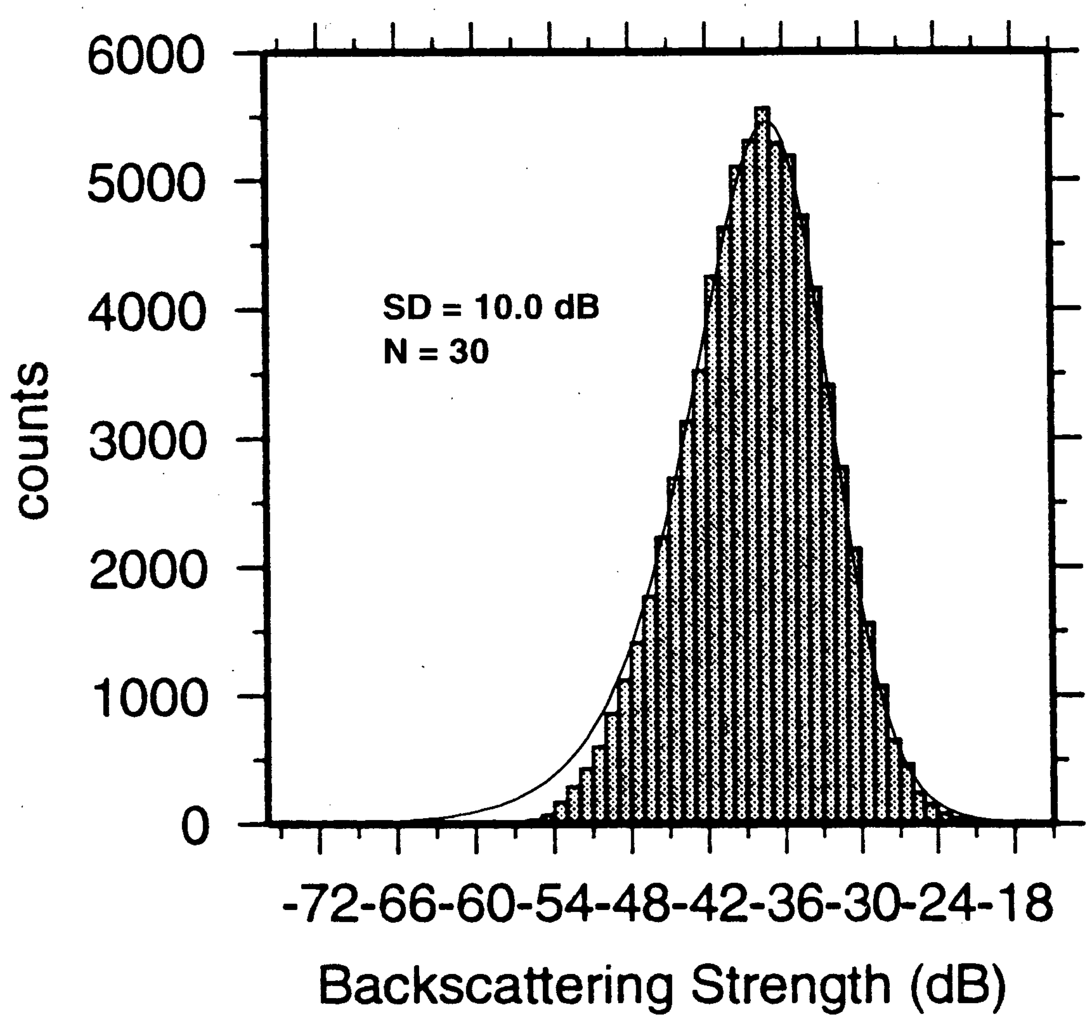
Wind 15m/sec



800 Hz   10 -> 20 DEG BIN

[Monjo et al., 1995]

Wind 15m/sec



800 Hz 10 -> 20 DEG BIN

[Monjo et al., 1995]

Remarks on Intensity Statistics Modeling

- Model: N independent scatterers in scattering area
- Need intensity pdf for single scatterer as function of environmental conditions
- Need number of effective scatterers per unit area as function of environmental conditions
- Should consider N as random variable
  - Need pdf for N per unit area

Modeling Low Frequency Surface Scatter Intensity Statistics

Appendix B

Eric I. Thorsos
Donald B. Percival
Kate M. Bader

Applied Physics Laboratory
College of Ocean and Fishery Sciences
University of Washington

Acoustical Society of America • Acoustical Society of Japan
Third Joint Meeting

Honolulu, Hawaii
2–6 December 1996

Work supported by ONR

Introduction

- Scattering strength $\leftrightarrow$ average scattered intensity
- Require other statistics, e.g., intensity pdf
- If acoustic field statistics are Gaussian, intensity will have exponential pdf
- CST results (Gauss, Huster) at low frequency (100 Hz – 1000 Hz) indicate intensity pdf has higher tail than exponential
- Cannot simply measure intensity pdf for direct use in model
  - Intensity pdf depends on the scattering area, i.e., on the number of scatterers

Topics to be discussed:

- Measurements of intensity pdf — ASREX
- Modeling the intensity pdf
  - Dependence on scattering area

Acoustic Surface Reverberation EXperiment (ASREX)

University of Miami

Harry A. Deferrari (P.I.)

Neil J. Williams

Date: December 93 – March 94 (84 days)

Location: 34° N, 70° W

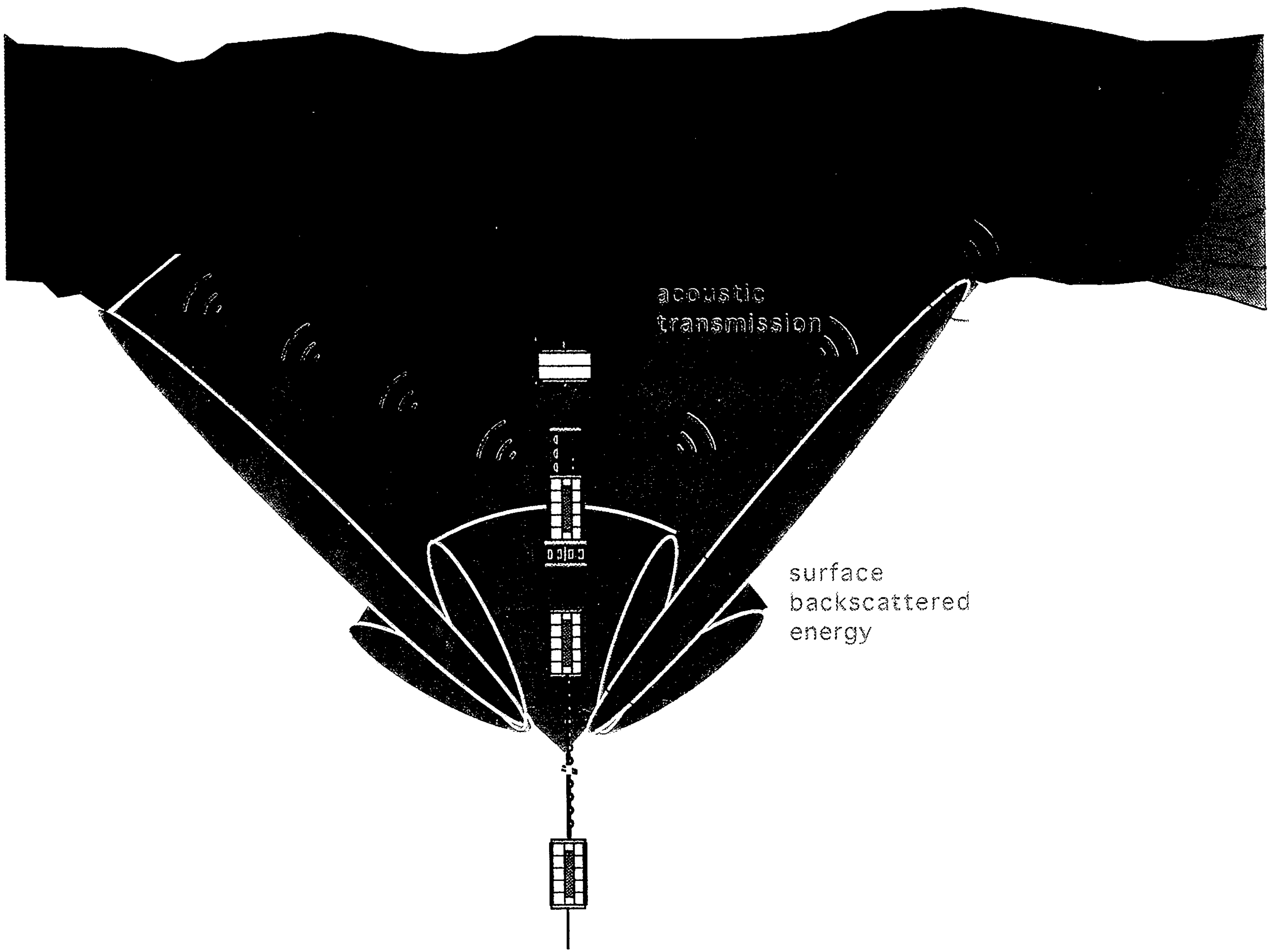
Frequencies: 100, 200, 400, 800 Hz

Transmissions every 12 minutes

Initial data analyzed for intensity statistics

- **Frequency: 800 Hz**
- **Time period: first 27 days**
- **Grazing angles: 10°–30°**
- **Pulse type: 13-digit Barker code**
- **Effective pulse length: 20 ms**

ASREX Acoustic Mooring
(University of Miami)



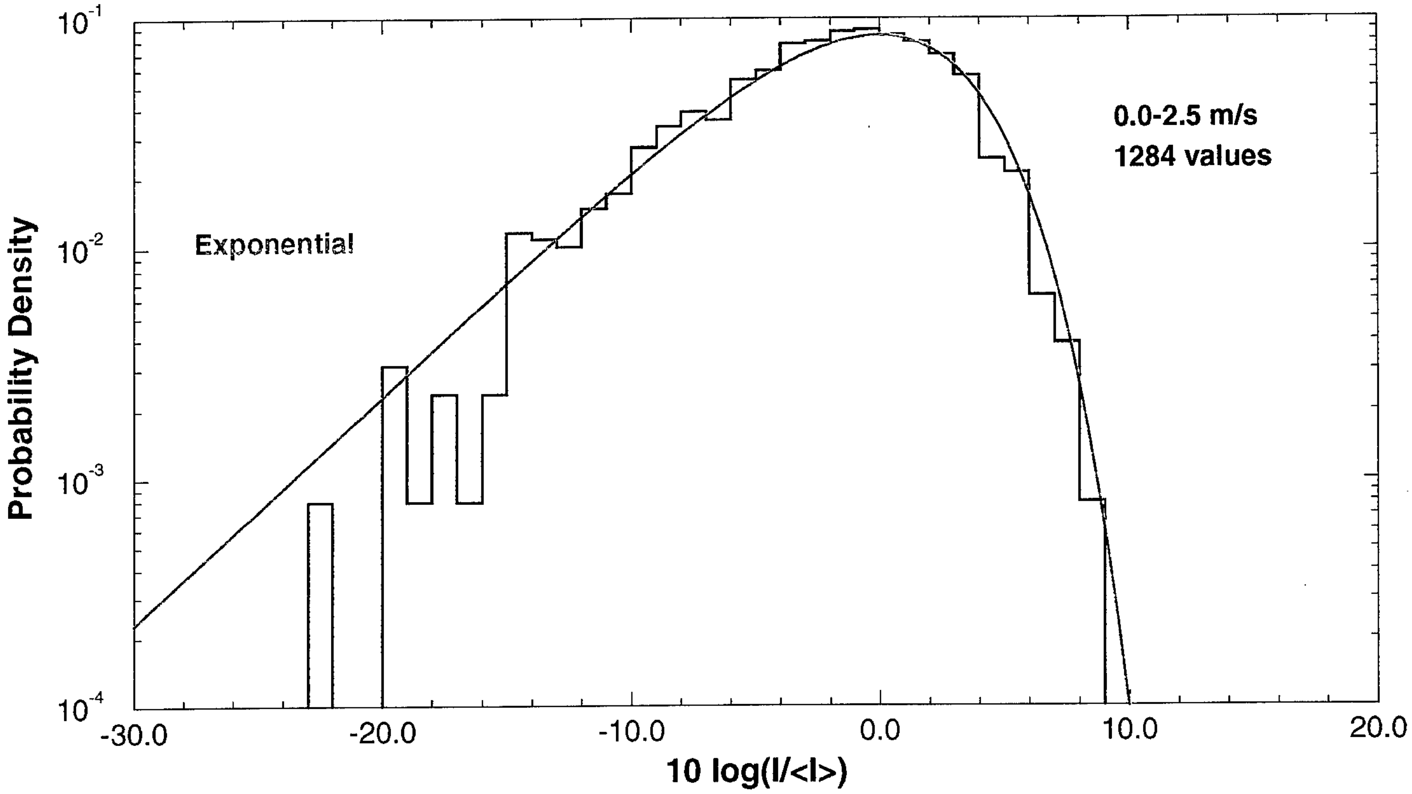
Histogram of Intensity Fluctuations

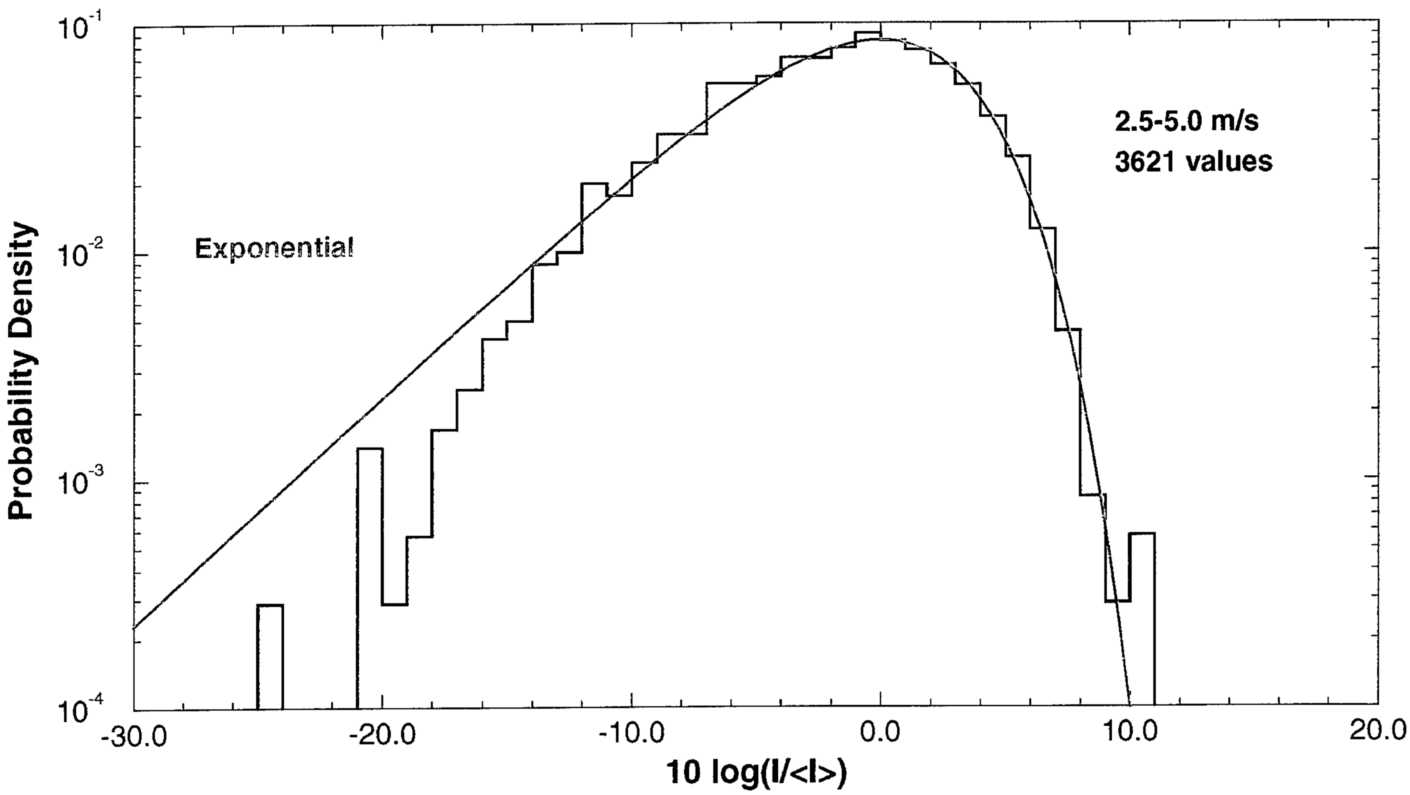
- Removal of deterministic trends
  - Intensities grouped into one-degree bins
  - Local intensity average obtained using 2-hour running means
  - Intensity fluctuations relative to local mean yield histogram

- Histograms conditioned on
  - Wind speed
  - SNR > 15 dB

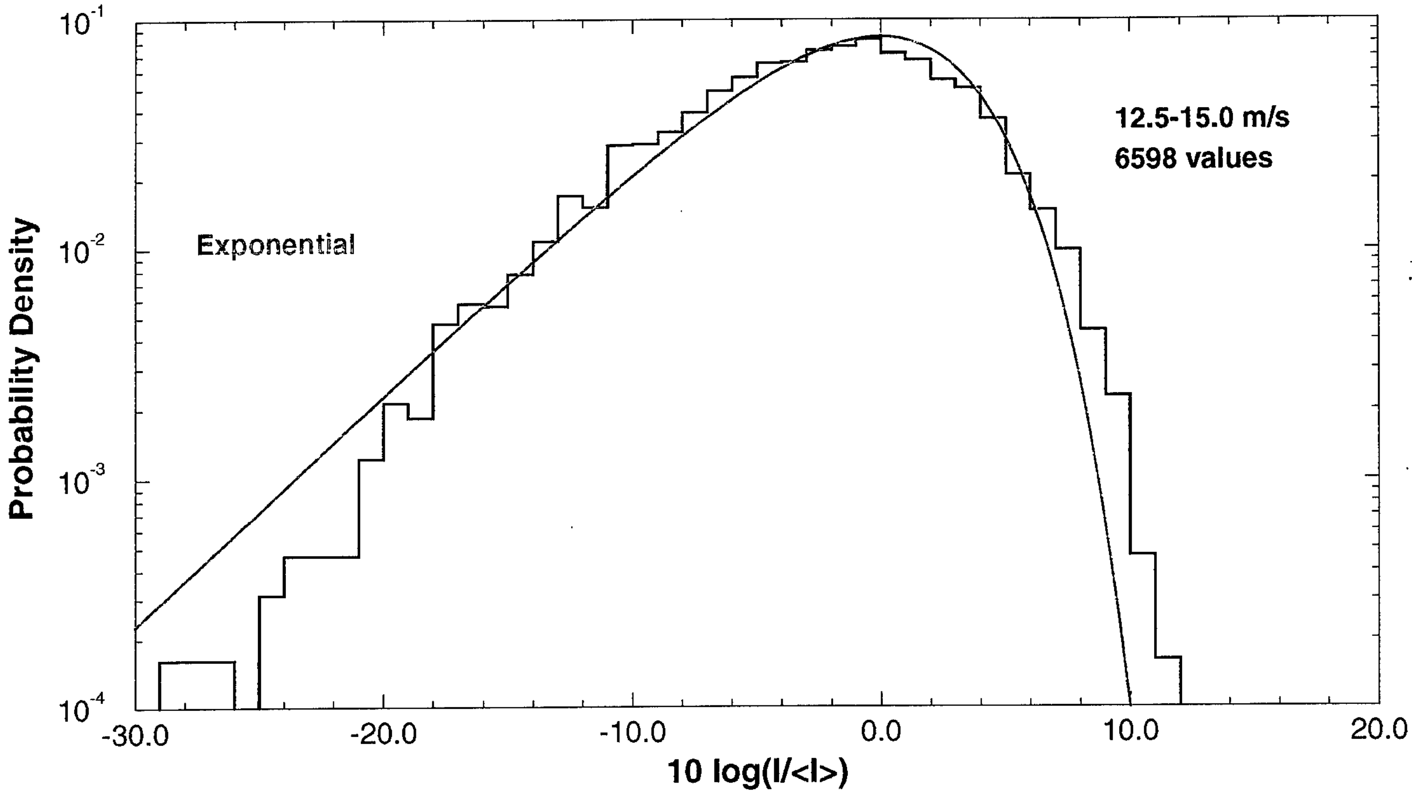
- Scattering area ~ 2–4 $\times$ 10^4 m^2

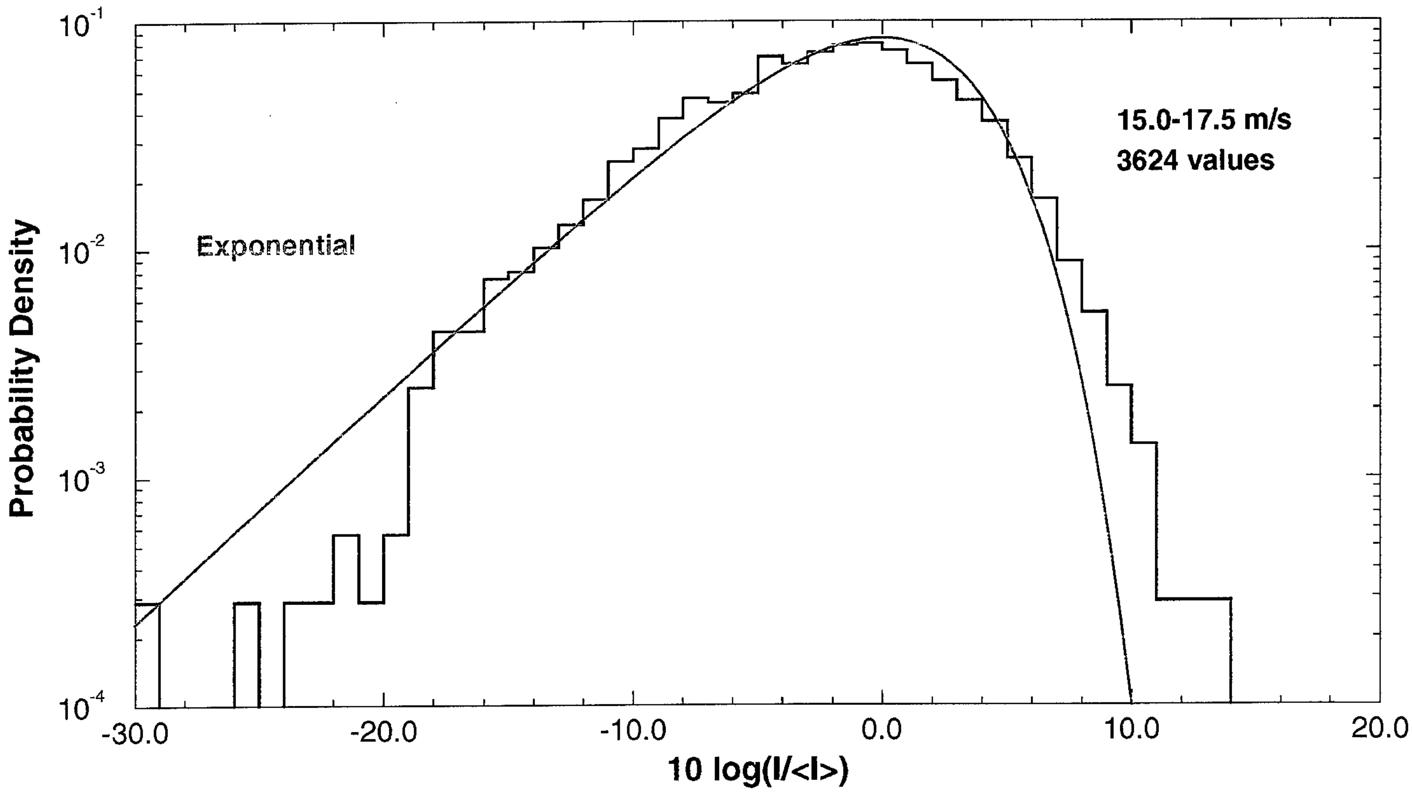
ASREX Intensity PDF
800 Hz, 10-30 Degrees, Days 353-380





ASREX Intensity PDF
800 Hz, 10-30 Degrees, Days 353-380

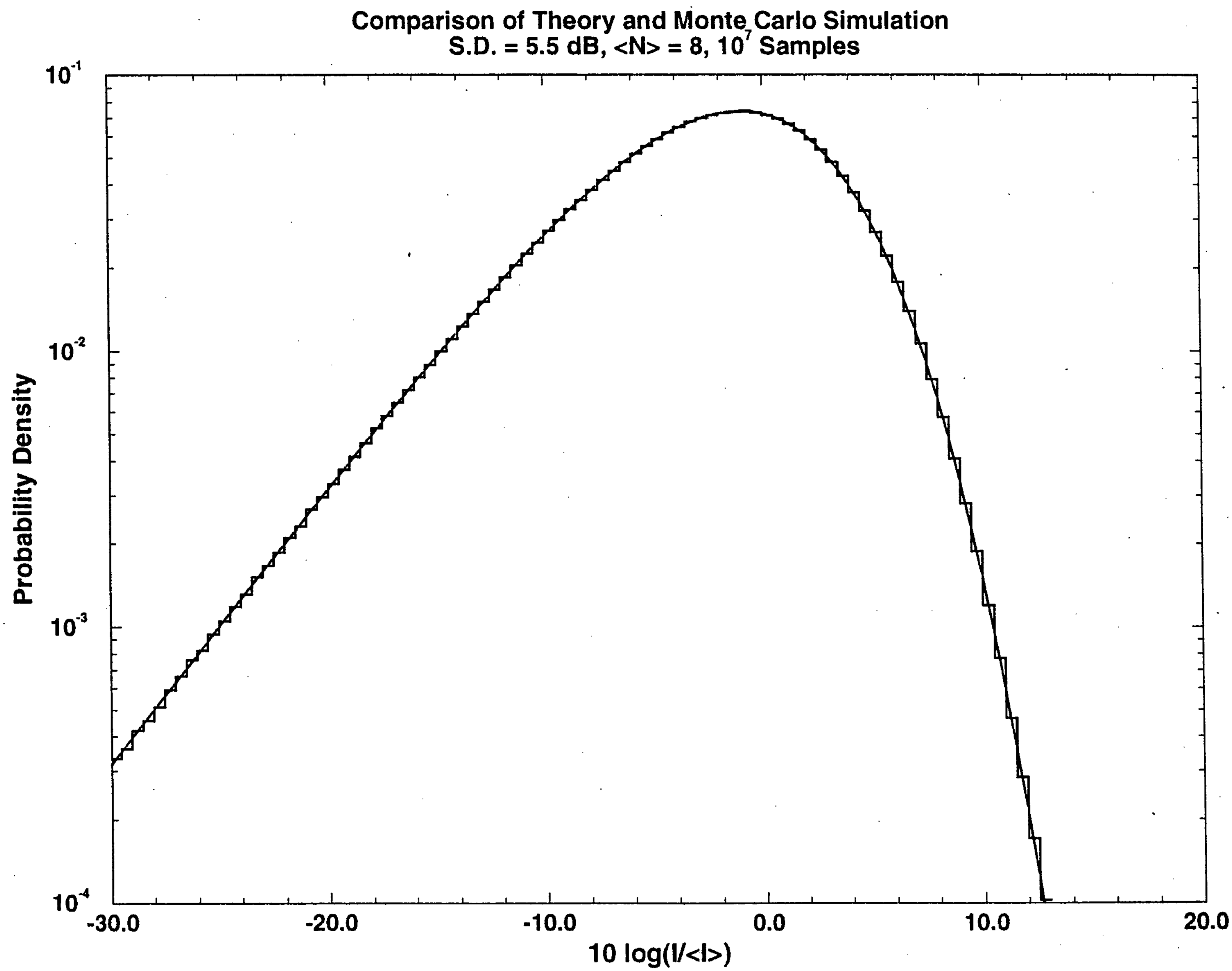


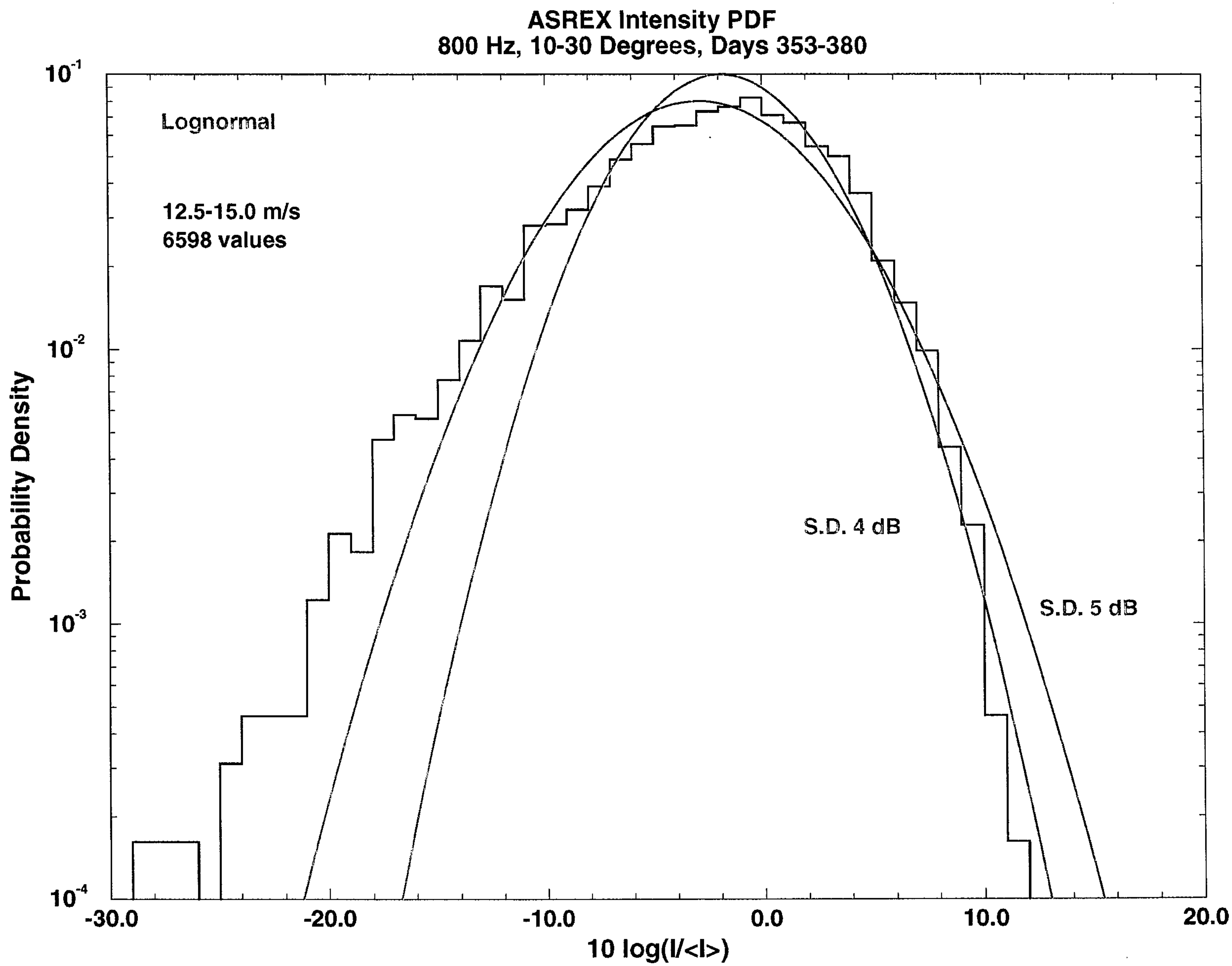


Modeling Surface Scatter Intensity PDF

Assumptions:

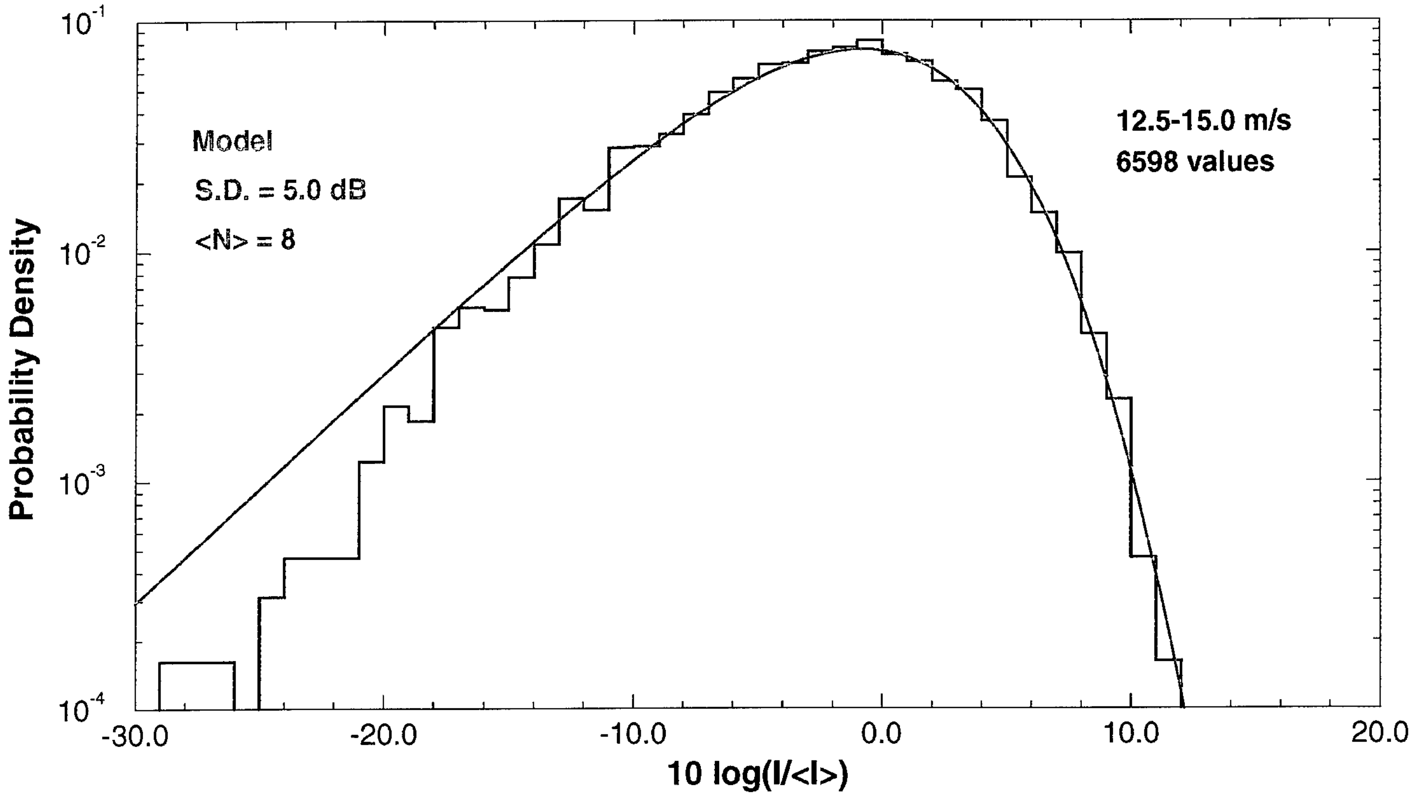
- Effective discrete scatterers
  - Scattered field a random variable
- Scattered intensities identically distributed for all scatterers
  - Bubble cloud scattering
  - Use lognormal distribution
  - Need to specify standard deviation
- Scattered phase uniformly distributed
- Scatterers randomly distributed spatially
  - Implies number of scatterers in a given area is Poisson distributed
  - Need to specify average number of scatterers per unit area

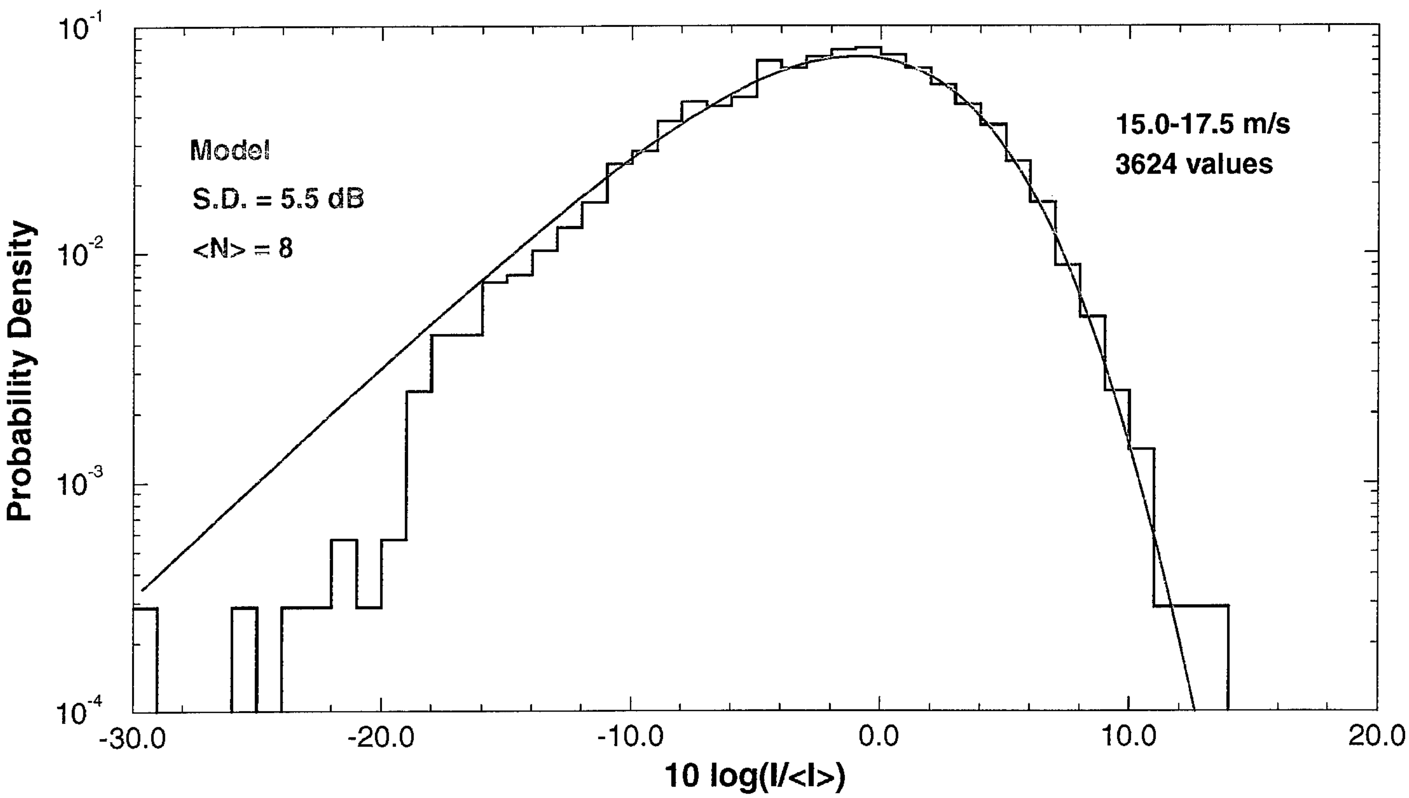

Comparison of Theory and Monte Carlo Simulation
S.D. = 5.5 dB, <N> = 8, 10^7 Samples
Probability Density
10^-1
10^-2
10^-3
10^-4
-30.0
-20.0
-10.0
0.0
10.0
20.0
10 log(I/<I>)



ASREX Intensity PDF
800 Hz, 10-30 Degrees, Days 353-380
Lognormal
12.5-15.0 m/s
6598 values
S.D. 4 dB
S.D. 5 dB
Probability Density
10 log(I/<I>)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
-30.0
-20.0
-10.0
0.0
10.0
20.0

ASREX Intensity PDF
800 Hz, 10-30 Degrees, Days 353-380





Summary

- Conditions: f = 800 Hz
  Grazing angles 10°–30°
  Scattering area ~ $2\text{–}4 \times 10^4$ m^2
- At low sea states (U < 5 m/s) intensity distribution is exponential
  - Region of interface scattering
- At higher sea states intensity distribution deviates from exponential with higher upper tail
  - Region of bubble cloud scattering
- Model can replicate ASREX intensity distributions, but
  - Model is underdetermined
  - Need to compare with data for smaller scattering areas